

Technical Report NASA Grant NAG 5-7151  
THE PHYSICAL ORIGIN OF GALAXY MORPHOLOGIES  
AND SCALING LAWS

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**Proposal Abstract NAG 5-7151**

We propose a numerical study designed to interpret the origin and evolution of galaxy properties revealed by space- and ground-based imaging and spectroscopical surveys. Our aim is to unravel the physical processes responsible for the development of different galaxy morphologies and for the establishment of scaling laws such as the Tully-Fisher relation for spirals and the Fundamental Plane of ellipticals. In particular, we plan to address the following major topics. (i) The morphology and observability of protogalaxies, and in particular the relationship between primordial galaxies and the  $z \sim 3$  "Ly-break" systems identified in the Hubble Deep Field and in ground-based searches. (ii) The origin of the disk and spheroidal components in galaxies, the timing and mode of their assembly, the corresponding evolution in galaxy morphologies and its sensitivity to cosmological parameters. (iii) The origin and redshift evolution of the scaling laws that link the mass, luminosity, size, stellar content, and metal abundances of galaxies of different morphological types. This investigation will use state-of-the-art N-body/gasdynamical codes to provide a spatially resolved description of the galaxy formation process in hierarchically clustering universes. Coupled with population synthesis techniques, our models can be used to provide synthetic "observations" that can be compared directly with observations of galaxies both nearby and at cosmologically significant distances. This study will thus provide insight into the nature of protogalaxies and into the formation process of galaxies like our own Milky Way. It will also help us to assess the cosmological significance of these observations within the context of hierarchical theories of galaxy formation and will supply a theoretical context within which current and future observations can be interpreted.

**Hardware Extension/Code development**

The grant budget includes \$ 21,600 for the purchase of 3 additional GRAPE-3Af boards (these are special purpose hardware for N-body integrations) in order to upgrade the available computing environment to a total of 5 GRAPE-3Af boards. The 3 additional boards were ordered in April and delivered in early July. Installation of the 3 additional board was straightforward. Our N-body/SPH code has now been adapted to support the full capabilities of the 5 GRAPE-3Af boards.

**Scientific Milestones**

- We performed a large series of ultra-high resolution simulations of the formation of galaxies. Different cosmological models as well as different star formation recipes have been explored. To our knowledge, this set of simulated galaxies is the largest and highest resolved sample performed up to date.

- We find that the slope and scatter of the I-band Tully-Fisher relation are well reproduced in the simulations, although not, as proposed in recent work, as a result of the cosmological equivalence between halo mass and circular velocity: large systematic variations in the fraction of baryons that collapse to form galaxies and in the ratio between halo and disk circular velocities are observed in our numerical experiments. The Tully-Fisher slope and scatter are recovered in this model as a direct result of the dynamical response of the halo to the assembly of the luminous component of the galaxy. We conclude that models that neglect the self-gravity of the disk and its influence on the detailed structure of the halo cannot be used to derive meaningful estimates of the scatter or slope of the Tully-Fisher relation.
- We applied our high resolution numerical simulations to make predictions on the properties and distribution of the high- $z$  progenitors of present day galaxies. The simulations indicate that for currently favored cosmologies most of the progenitors of present day galaxies are predicted to be too dim ( $m_R > 25.5$ ) to be identified with the observed population of spectroscopically confirmed Lyman-break galaxies and rather correspond to the low luminosity end of the high- $z$  luminosity function, consistent with earlier findings. A substantial fraction of galaxies have several detectable ( $m_R < 28$ ) progenitors at redshift three, which are typical spread over a volume of several hundred kpc.
- In a recent work, we presented the first ever cosmological simulation capable of reproducing the variety of galaxy morphologies that is observed in the universe. We show that a single galaxy in the CDM cosmogony may run through the whole Hubble sequence during its lifetime validating previous theoretical speculation and illustrating the inextricable link between morphology and the hierarchical mode of galaxy formation. The perplexing variety of galaxy morphologies is highly suggestive of—and may actually even demand—a universe where structures have evolved hierarchically.
- In a collaboration with M. Haehnelt (Cambridge), M. Rauch (Carnegie), MS combined prediction for several hierarchical cosmogonies with observational evidence on damped Lyman-alpha systems (DLAS) in order to establish a correspondence between the high redshift galaxy population and the properties of DLAS. The main conclusions are: (i) predicted impact parameters between damped absorption systems and the luminous parts of the absorbing galaxy are expected to be very small (0.3''-1'') for most galaxies. (ii) luminosities of galaxies causing damped absorption are generally fainter than  $m_R = 25$  and thus correspond to the faint end of the galaxy luminosity function. DLAS should currently provide the best probe of the progenitors of normal present-day galaxies.
- In collaboration with V. Eke, we studied the properties of Cold Dark Matter (CDM) halos formed in numerical simulations, with particular emphasis on the dependence of halo concentrations upon the amplitude and shape of the power spectrum of density fluctuations. This work showed that, contrary to earlier findings, the amount of mass within the central  $\sim 10$  kpc of the CDM halos is not too large to be consistent with that inferred for the Milky Way, or a sample of local 'Tully-Fisher' galaxies. It was demonstrated that the difference with earlier findings was a result of an erroneously high normalisation of the power spectrum of density fluctuations in the previous work. Consequently, when the fluctuations are tuned to reproduce the observed local abundance of galaxy clusters, the formation redshifts of galaxies become smaller, as do their central density concentrations. This work was extended to include Warm Dark Matter (WDM) power spectra, and a model was presented that could accurately predict both the mass-dependence and the redshift-dependence of the halo concentrations for WDM and CDM power spectra.

- With Chris Gottbrath, a graduate student at Steward Observatory, we have investigated how the structure of dark matter halos is affected by a central galactic disk. It could be shown that the so-called adiabatic contraction, a technique widely used in semi-analytical studies, can even quantitatively reproduce the results seen in high resolution numerical simulations. A study on whether the presence of central galactic disk can significantly change the triaxial shape of dark matter halos gave inconclusive results.

## Publications:

### Refereed publications

- Steinmetz, M., Navarro, J.F., 1999, "The cosmological origin of the Tully-Fisher relation", ApJ, 513, 555
- Steinmetz, M., 2000, "Numerical Simulations of Galaxy Formation" Astrophysics and Space Sciences, 2000, 269, 513.
- Navarro, J.F., Steinmetz, M., 2000, "The Core Density of Dark Matter Halos: A Critical Challenge to the Lambda-CDM Paradigm?", ApJ 528, 607
- Haehnelt, M.G., Steinmetz, M., Rauch, M., 2000, "Damped Lyman alpha absorber and the faint end of the galaxy luminosity function at high redshift", ApJ 534, 594
- Navarro, J.F., Steinmetz, M., 2000, "Dark Halo and Disk Galaxy Scaling Laws in Hierarchical Universes", ApJ 538, 477
- Eke, V.R., Navarro, J.F., Steinmetz, M., 2001, "The Power Spectrum Dependence of Dark Matter Halo Concentrations", ApJ 554, 114
- Steinmetz, M., Navarro, J.F., 2002, "The Hierarchical Origin of Galaxy Morphologies", New Astronomy, 7/4, 155.
- Bradac, M., Schneider, P., M. Steinmetz, M., Lombardi, M., King, L.J., Porcas, R., 2002, "B1422+231: The influence of mass substructure on strong lensing", Astronomy and Astrophysics, 388, 373.
- Gottbrath, C., Steinmetz, M., Navarro, J.F., 2002, "The influence of galactic disks on the density profiles of dark matter halos" in preparation.
- Steinmetz, M., Navarro, J.F., 2002, "The high-redshift progenitors of present day field galaxies" in preparation

### Conference proceedings

Steinmetz, M., Navarro, J.F., 1999, "The Cosmological Origin of Disk Galaxy Scaling Laws", Proceedings of the 15th IAP Astrophysics Colloquium *Dynamics of galaxies: from the Early Universe to the Present*, July 9-13, 1999, eds. F. Combes, G.A. Mamon, and V. Charmandaris, Astronomical Society of the Pacific Conference Series Vol. 197, p. 165.

Steinmetz, M., 2001, "The Hierarchical Origin of Galaxy Morphologies", Proceedings of the Conference Dwarf Galaxies and their Environment, eds. K.S. deBoer, R.-J. Dettmar, U. Klein, Bad Honnef, Germany, January 23-27, 2001, p. 297

Steinmetz, M., 2001, "Numerical Simulation of Galaxy Formation: The Properties of High Redshift Galaxies", Proceedings of the Conference Gas and Galaxy Evolution, A Conference in Honor of the 20th Anniversary of the VLA, eds. J.E. Hibbard, M.P. Rupen, J.H. van Gorkom, Socorro, New Mexico, May 21-24, 2000, Astronomical Society of the Pacific Conference Series Vol. 240, p. 79

Navarro, J.F., 2001, "Dark Halo and Disk Galaxy Scaling Laws", Proceedings of the Conference Galaxy Disks and Disk Galaxies, eds. J.G. Funes, S.J. and E. Maria Corsini, Rome, Italy, June 12-16, 2000, Astronomical Society of the Pacific Conference Series Vol. 230., p. 527

Steinmetz, M., 2001, "Numerical Simulation of Galaxy Formation", Proceedings of the Conference Galaxy Disks and Disk Galaxies, eds. J.G. Funes, S.J. and E. Maria Corsini, Rome, Italy, June 12-16, 2000, Astronomical Society of the Pacific Conference Series Vol. 230, p. 633

Steinmetz, M., 2001, "The Cosmological Origin of Disk Galaxy Scaling Laws", Proceedings of the workshop The Physics of Galaxy Formation, eds. M. Umemura and H. Susa, Tokyo, July 3-7, 2000, Astronomical Society of the Pacific Conference Series Vol. 222, p. 209)

Steinmetz, M., 2002, "Numerical studies of galaxy formation using special purpose hardware", Invited review presented at the IAU Symposium 208 Astrophysical Supercomputing using Particle Simulations, Tokyo, July 2001, in press.

Navarro, J.F., 2002, "The Hierarchical Origin of Galaxy Morphologies and Scaling Laws", Proceedings of "Disks of Galaxies: Kinematics, Dynamics and Perturbations", ASP Conference Series. E. Athanassoula & A. Bosma, eds.

#### Invited talks at Conferences

Review talks are marked by a \*, MS=M. Steinmetz, JN= J.F. Navarro

\*JN: IX International Astronomical Union Regional Meeting, Puebla, Mexico, November 1998.

\*MS: "Local Group" Aspen Winter Conference, January 1999.

\*JN: ESO Very Large Telescope Opening Symposium, Antofagasta, Chile, March 1999.

\*MS: "Hydrodynamic Aspects of Galaxy Formation", Leiden, The Netherlands, March 1999.

\*JN: "Cosmology and Gravitation", Banff, Canada, May 1999.

JN: Ringberg Workshop on Satellite Galaxies, Ringberg Castle, Tegernsee, Germany, June 1999.

\*MS: "Galaxy dynamics: from early times to the present" Paris, France, July 1999.

MS: "Galaxies in the Young Universe", Ringberg Castle, Tegernsee, Germany, August 1999.

\*MS: "A new millennium in galaxy morphology: from  $z=0$  to the Lyman break" International keynote review speaker, Johannesburg, South Africa, September 1999.

\*JN: Workshop on Disk Galaxies, Max-Planck-Institut für Astronomie, Heidelberg, Germany, October 1999.

\*JN: "Cosmology and Gravitation", Banff, Canada, February 2000.

\*MS: "Cosmology and Gravitation", Banff, Canada, February 2000.

\*JN: "Galaxy Formation and Evolution", Santa Barbara, March 2000.

MS: "Galaxy Formation and Evolution", chairman of a podium discussion Dark Matter Halos and Galactic Rotation Curves - Is There a Problem?, Santa Barbara, March 2000.

JN: Astrophysics Conference, Centro de Estudios Científicos del Sur, Valdivia, Chile. April 2000.

JN: Oort Symposium, Leiden. April 2000.

\*MS: "Gas and Galaxy Evolution", a Conference in Honor of the 20th Anniversary of the VLA, Socorro, New Mexico, May 2000.

JN: American Physics Society Annual Meeting, Eugene, Oregon, May 2000.

JN: XIX International Conference on Neutrino Physics and Astrophysics, Sudbury, Canada, June 2000.

\*JN: "Galaxy Disks and Disk Galaxies", Rome, Italy, June 2000.

\*MS: "Galaxy Disks and Disk Galaxies", Rome, Italy, June 2000.

\*MS: "The Physics of Galaxy Formation", Tsukuba International Workshop, Tokyo, July 2000.

\*MS: Victoria Computational Cosmology Conference, Victoria, Canada, August 2000.

\*JN IAG-USP Advanced School on Astrophysics. 2-6 September 2000. Angra dos Reis, Rio de Janeiro, Brazil. September 2000.

\*MS: "Dwarf Galaxies and their Environment", Bad Honnef, Germany, January 2001.

MS: Aspen Winter Conference, January 2001.

\*JN: "Cosmology and Gravitation", Banff, Canada, February 2001.

\*MS: APS April Meeting, April 2001.

\*JN: Workshop on Galaxy and Halo Shapes, Yale, May 2001.

\*JN: Princeton Workshop on Dark Matter, May 2001.

\*MS: Princeton Workshop on Dark Matter, May 2001.

\*JN: IAU Symposium 208 "Astrophysical Supercomputing using Particle Simulations" Tokyo, July 2001.

\*MS: IAU Symposium 208 "Astrophysical Supercomputing using Particle Simulations" Tokyo, July 2001.

MS: "The Mass of Galaxies at Low and High Redshift", Venice, October 2001.

JN: "Disks of Galaxies: Kinematics, Dynamics and Perturbations", Puebla, Mexico, November 2001.

MS: "Structure and Formation of Giant Elliptical Galaxies", Ringberg Castle, Tegernsee, Germany, November 2001.

JN: "Galaxy Evolution: Theory and Observations", Cozumel, Mexico, April 2002.

#### Colloquia

JN: University of California, Berkeley, February 1999

JN: University of British Columbia, March 1999

MS: University of Colorado, April 1999

JN: Max-Planck-Institut für Astrophysik, June 1999

MS: MPI für Astronomie, July 1999  
 JN: University of Victoria, October 1999  
 MS: Fermilab, October 1999  
 MS: University of California, San Diego, February 2000  
 MS: Institute for Advanced Study, Princeton, April 2000  
 MS: Johns-Hopkins University, Baltimore, April 2000  
 MS: Osservatorio Astrofisico di Arcetri, Florence, June 2000  
 MS: University of Arizona, Tucson, September 2000  
 JN: Observatorio Nacional, Universidad Nacional de Córdoba, Argentina, October 2000  
 MS: New Mexico State University, November 2000  
 MS: Carnegie Observatories, Pasadena, November 2000  
 MS: Universität Hamburg, November 2000  
 MS: Universität Zuerich, November 2000  
 MS: Astrophysikalisches Institut Potsdam, December 2000  
 MS: MPI für Radioastronomie Bonn, May 2001  
 JN: Durham University, May 2001  
 MS: Heidelberg Astronomisches Kolloquium, May 2001  
 MS: Universität Göttingen, Juni 2001  
 JN: University of Illinois, October 2001  
 JN: Cornell University, December 2001  
 JN: New York University, December 2001  
 JN: University of Arizona, February 2002  
 JN: University of Massachusetts, February 2002  
 MS: Munich Joint Astronomical Colloquium, April 2002  
 JN: Herzberg Institute for Astrophysics, Victoria, April 2002  
 MS: Astrophysikalisches Institut Potsdam, May 2002

## Students

**Advising:** 5 undergraduate (Pizagno (graduate student at Ohio State since 8/99), Fields (graduate student at Ohio State since 8/00), Michaels, Rudd, Shaked) ) and 7 graduate students (Bailin, Gottbrath, Kohnenkamp, Saga, Scott, Sharma, Lennek)

## Second year projects (completed):

J. Bailin: Tidal torques and the structure of disk galaxies.  
 C. Gottbrath: The influence of luminous galaxies on the structure of dark matter halos.  
 I. Kohnenkamp: Numerical simulations of the large scale structure of the universe using special purpose hardware.

**Second year projects (in progress):**

M. Lennek: Fast bars and the dark mass content of disk galaxies.

**Independent Studies (completed):**

D. Rudd (senior): Load balance optimization of a parallel treecode

D. Fields (senior): Classification of substructure in X-ray clusters

D. Michaels (senior): Numerical studies on the morphology-density relation in galaxy clusters

J. Pizagno (senior): Dynamics of merging dark matter halos in cosmological N-body simulations

D. Saga (grad, physics): Modelling deep exposures at the next generation Space Telescope (NGST)

**Dissertations (completed):**

J. Scott: Calibrating the intergalactic UV background by combining observations of the proximity effect with numerical simulations of the Lyman- $\alpha$  forest.

**Dissertations (in progress):**

J. Bailin: Tidal torques and the structure of disk galaxies.

S. Sharma (Physics): The angular momentum distribution of dark matter halos.